Intensity and Damage Assessment of the 2007 Tocopilla Earthquake, Chile.

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This report presents the findings of the reconnaissance team from three Chilean universities that conducted site visits to approximately 20 towns in the earthquake zone shortly after the event. The focus was primarily on damage to dwellings and lifelines, geotechnical effects and the calculation of intensities.

Introduction

At 12:40 a.m. local time on November 14th, 2007, a Ms 7.5 (M_W 7.7) earthquake struck the northern coast of Chile, about 51 km north-east of the city of Mejillones (60 km from Antofagasta). Twenty six aftershocks with a magnitude greater than 5.0 were recorded during the first fifteen days after the earthquake. There were two fatalities and at least 45 people injured.

The damage zone extended from the Guatacondo gorge to the city of Antofagasta. The region is part of the Atacama desert and, since the middle of the nineteenth century, it has been inhabited mainly by workers in the nitrate mines. Today, only 8% of the regional population lives in the interior towns. In the last fifty years, there has been significant migration to the coastal cities of Tocopilla, Mejillones and Antofagasta.

Much of the damage occurred in Tocopilla, a city of 25,000 inhabitants and the most populated city in the area affected by the earthquake. The buildings which sustained more damage were one story self-construction dwellings. Hospitals, schools, and other public buildings sustained moderate to severe damage. Some of these buildings had been previously damaged in the earthquake of December 1967 (Ms=7.3). Highways and urban roads suffered slight damage due to landslides and rock falls.

Geology

Located between latitudes 21º and 24º South in northern Chile, the damaged region has four main morphostructures with north-south orientation. These are the Cordillera de Los Andes, the Precordillera, the Central Valley and the Coastal Cordillera (see Figure 1). Most of the towns surveyed during the visits are located on quaternary-aged alluvial and fluvial deposits on the Coast and the Central Valley.

The Central Valley is a N-S trending elongated basin with a mean altitude of 1,300 m. Here the superficial deposits are fluvial silty sands with gravel and alluvial deposits of fine soils interbedded with thin coarse-grained soil layers.

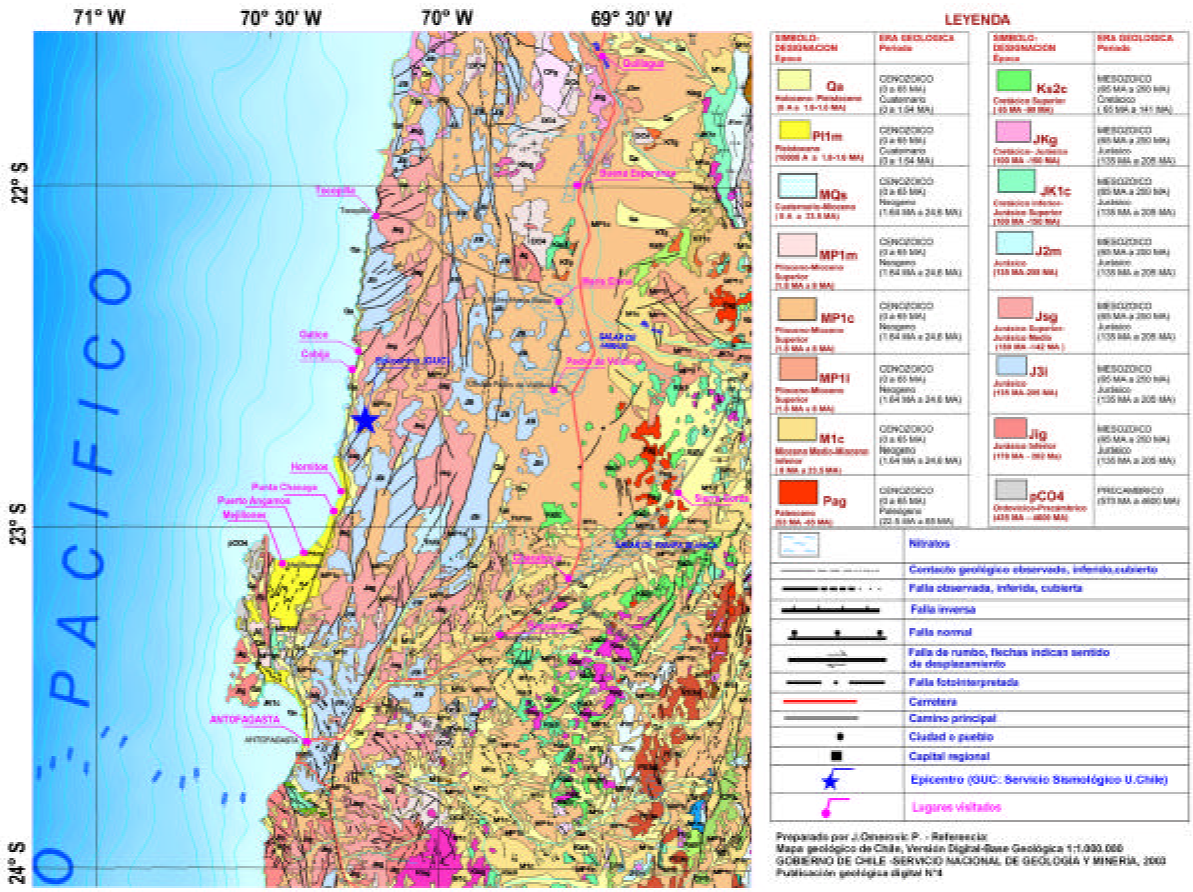


Figure 1 - Geological map (Modified from SERNAGEOMIN, 2003)

Tectonics/Strong Ground Motion

The Tocopilla earthquake was the result of the subduction of the Nazca plate under the South American continental plate. This plate interaction generates significant seismic activity along the coasts of Peru and Chile. The earthquake was an interplate event and occurred to the north of the 1995 Antofagasta earthquake rupture area. The region is a highly active subduction zone where many large subduction interplate earthquakes have occurred during the last century (Comte and Pardo, 1991).

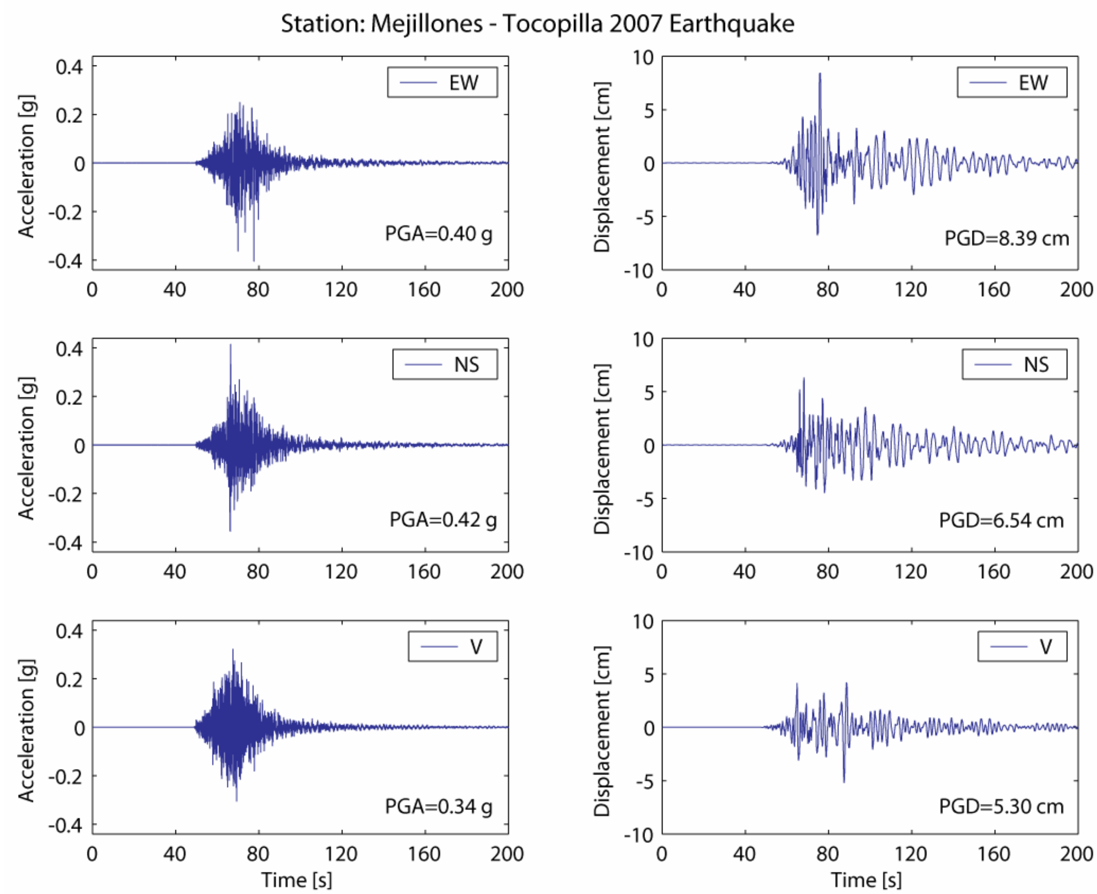
The earthquake had a moment magnitude (Mw) of 7.7 (NEIC), and the hypocenter was located at 22°41´31"S and 70°12´54"W, at a depth of 39 km (Barrientos, 2007). Fault rupture propagated to the south from the hypocenter between Tocopilla and Mejillones and is approximately 100 km in length. The locations of the aftershock hypocenters match this fault plane (Barrientos, 2007). The cities most affected lie within the ground surface projection of the fault plane.

The earthquake was recorded at several strong motion stations in a variety of geologic site conditions. The station´s hypocentral distance D_H and horizontal and vertical recorded peak ground accelerations (PGA) are shown in Table 1. The ratio of vertical (VPGA) to horizontal PGA (HPGA) ranges from approximately 0.2 (*Copiapó*) to 1.0 (*Tocopilla-Gobernacion*), making the seismic code (INN, 1996) ratio (VPGA=2/3 HPGA) inaccurate in this case. It was observed that the degree of seismic wave amplifications was affected by the site soil condition (i.e., rock at Tocopilla-SQM and stiff soil at Tocopilla Gobernación).

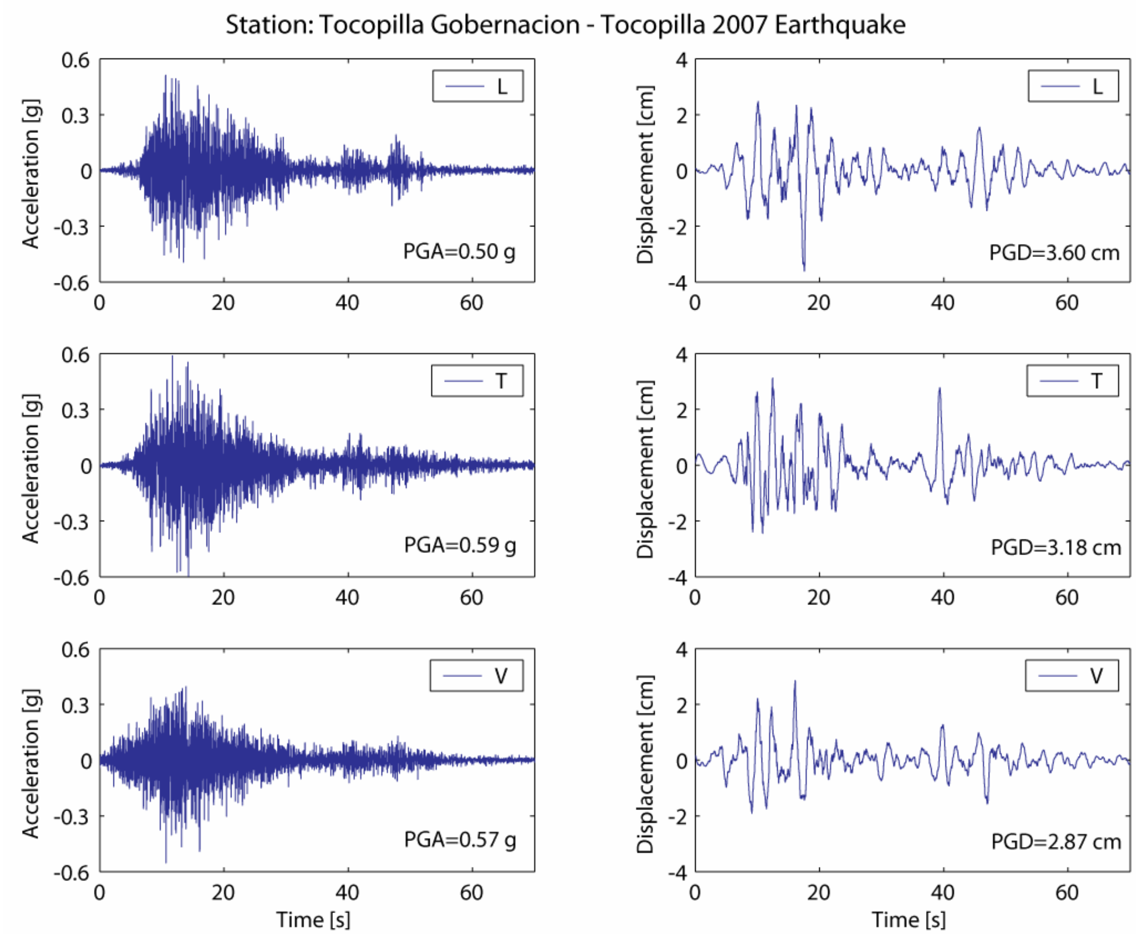
Table 1 – Peak ground accelerations of the Tocopilla Earthquake, November 2007 (Boroschek et al. 2008).

Station	**D_H [km]**	**HPGA [g]**	**VPGA [g]**
Calama	140	0.09	0.07
Mejillones	64	0.42	0.34
Punta Patache	213	0.08	0.06
Pica	262	0.20	0.10
Antofagasta	115	0.13	0.06
Iquique - Hospital	278	0.07	0.04
Iquique - Esc. Pub. Chipana	278	0.11	0.06
Tocopilla - SQM	78	0.35	0.16
Tocopilla - Gobernación	78	0.59	0.57
Tocopilla - Consultorio	78	0.39	0.17
San Pedro de Atacama	211	0.07	0.04
Baquedano	90	0.09	0.04
Alto Hospicio	275	0.09	0.07
Calama	140	0.09	0.07
Copiapó	522	0.05	0.01

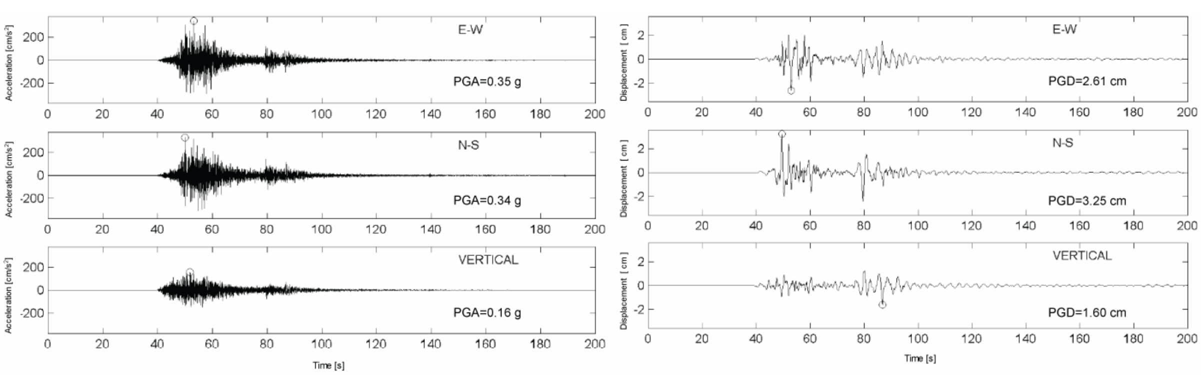
The acceleration records from the stations closest to the epicenter (Tocopilla and Mejillones) are shown in Figure 2. Two phases of strong motion are apparent, corresponding to slip along two asperities in the finite fault solution (Zeng et al., 2007; Salden, 2007). Notwithstanding the large peak acceleration, damage to the buildings where the ground motion record was registered was minimal in *Mejillones* and *Tocopilla-SQM* and moderate in *Tocopilla – Gobernación.* Figure 3 shows the post earthquake condition of the buildings. Figures 4a, 4b and 4c show the spectral acceleration responses of these records, for a damping ratio of 5%, indicating that rigid structures were likely to be the most damaged by this earthquake. All the strong motion records have long duration, about 150 seconds, with a strong motion phase of 20 sec (Boroschek et al., 2007).



a) Mejillones Station



b) Tocopilla-Gobernación Station



c) Tocopilla-SQM Station

Figure 2 - Acceleration time history at Tocopilla and Mejillones stations (Boroschek et al. 2008).

Accelerograph location in the Mejillones Health Center.

View of undamaged health center in Mejillones where the accelerograph is located.

View of the Gobernacion buildings in Tocopilla where the accelerograp is located

Moderate damage in short columns of the Gobernacion building.

View of some buildings near the accelero graph location on rock in Tocopilla.

View of undamaged thermoelectrical plant near the station located on rock in Tocopilla.

Figure 3 – Condition of buildings where ground motion records were obtained.

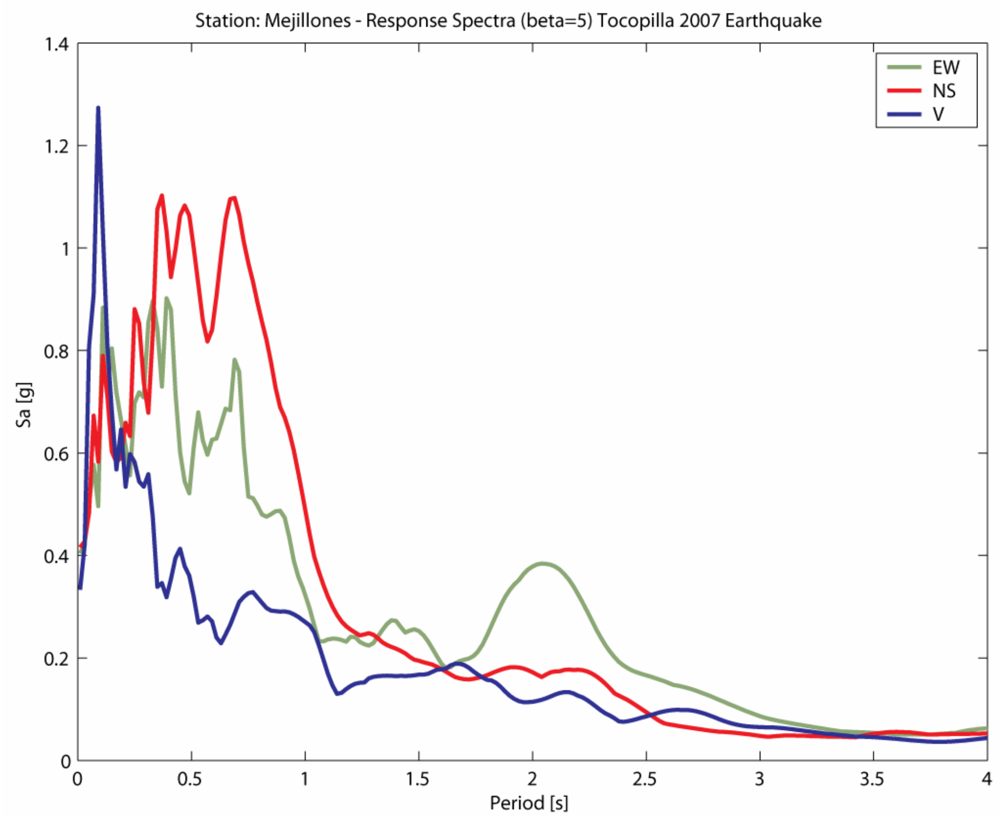


Figure 4a – Spectral acceleration response, 5% damping . Mejillones Station.

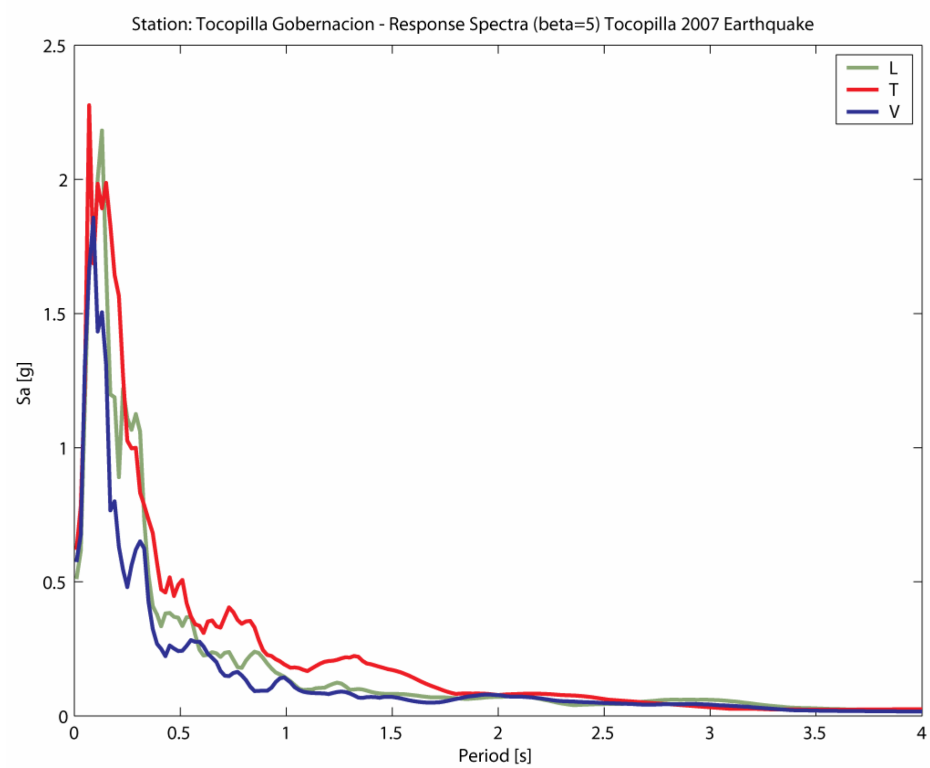


Figure 4b – Spectral acceleration response, 5% damping . Tocopilla-Gobernacion Station.

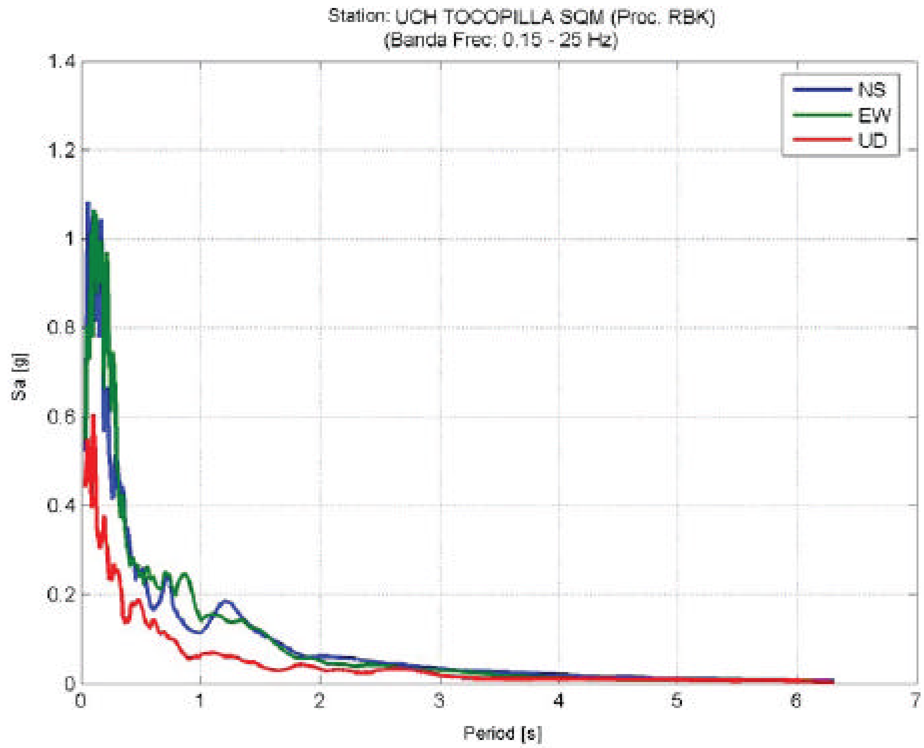


Figure 4c – Spectral acceleration response, 5% damping . Tocopilla-SQM Station (Boroschek et al., 2007).

In order to verify the kindness of the attenuation relationship proposed for Chilean interplate subduction earthquakes (Ruiz and Saragoni, 2005), in the Figure 5 can observed that the November 2007 Tocopilla peak ground accelerations are reasonably well represented by the Ruiz-Saragoni attenuation relationship for stiff soil and Ms = 7.5.

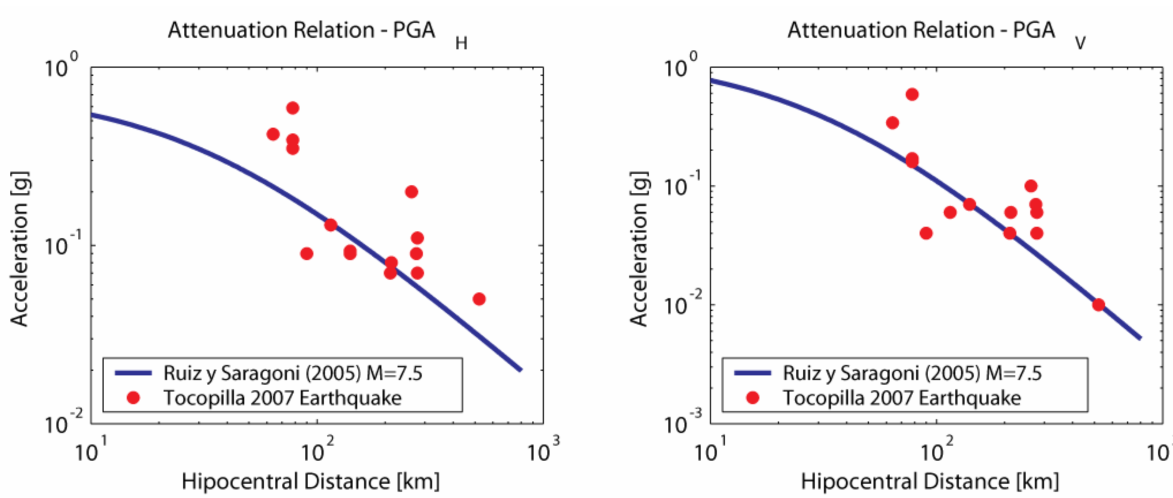


Figura 5 – Comparison of recorded peak ground aceleration data and the attenuation relationship proposed for stiff soil for Chilean interplate subduction earthquakes (Ruiz and Saragoni, 2005)

Geotechnical Aspects

Serious geotechnical hazards were not found although some landslides and pavement cracking were observed (see Figures 6 and 7). The landslides occured in road cuttings and natural slopes and caused the closure of Highway 1 between Tocopilla and Iquique (see Figure 8). No sand boils or other signs of soil liquefaction were observed near the coast.

Figure 6 – Landslide and pavement cracking on Highway 1.

Figure 7 – Landslide at Hornitos beach

Figure 8 – Landslide at La Paragua, Highway 1 between Tocopilla and Iquique (20 km from Tocopilla).

The hillside residential area of Tocopilla, located on the eastern side of the city, experienced some slope failures during the earthquake. Construction and retaining wall in the area have been carried out by homeowners cutting into the hillside and using the resulting material as fill. In some places the retaining wall had failed with the soil mass sliding downwards a short distance. Significant damage to structures due to slope and retaining wall deformations was observed along the hillside. Figure 9 shows some of these failures.

Figure 9 - Damage to the hillside residential area of Tocopilla.

Types of Construction and Damage

Most of the dwellings in the area are one story buildings. The dwellings over 50 years old are made of adobe and wooden frame with adobe or low quality concrete infill. Newer constructions are of reinforced or confined masonry (see Figure 10).

a). House made of adobe in Sierra Gorda

b) Wooden frame with adobe infill in Quillagua.

c) Wooden frame with low quality concrete infill in Maria Elena.

d) Confined masonry house in Mejillones

Figure 10. Types of construction:(a) Adobe, (b, c) Infilled wooden frame, and (d) Structural masonry.

Adobe: Adobe units are made with low plasticity fine silts. Although no reinforcement is included, few buildings made of adobe collapsed in the epicentral zone. This type of construction is more common in central Chile.

Wood frame with adobe infill: In this type of construction void spaces between wooden frames are filled with vertically aligned adobe units covered with mud plaster. Moderate damage to stucco or fallen adobe units was observed. Most of this construction is found in towns near Highway 5.

Wood frame with low quality concrete infill: In this case, wooden frames are filled with low quality concrete reinforced with a wire mesh, see Figure 11. Generally, the quality of the connections is good and the seismic perfomance is satisfactory. Fine vertical and diagonal cracks in the contact between the frame and the concrete were observed. This type of construction is found in Mejillones and Tocopilla, as well as the nitrate towns of Maria Elena and Pedro Valdivia.

Wire mesh reinforcement

Connection between wooden elements

Figure 11 – Details of a house made with wooden frames with low quality concrete infill.

The seismic performance of this type of self-construction dwellings is poor because the resisting elements (vertical and horizontal) are not assembled adequately.

Masonry: When properly designed and built, masonry walls of concrete block resisted the earthquake with little or no damage. However, the observed behavior was less satisfactory when the quality of the construction procedure and materials was poor, or the reinforcement detailing inadequate.

(a)

(b)

(c)

(d)

Figure 12. Observed damage: (a) Adobe house in Maria Elena, (b) Wooden frame with adobe infill in Baquedano, (c) Self-construction wooden frame with low quality concrete infill in Tocopilla and (d) Masonry in Maria Elena.

Lifelines

Water

In general, lifelines sustained relatively little damage with the exception of the water system in Tocopilla. The water for the city comes from the Topater Plant in Calama, through a 133 km long steel pipeline. The pipeline is divided into three sections separated by storage tanks, terminating in a tank located in the north of the city. Damage occurred in the connections and the longitudinal welds in the steel surface pipeline and in the pipe that connects the Esmeralda regulation storage tank with the valve chamber. The steel surface pipeline was also damaged by landslides. Additionally, connections in the asbestos-cement (AC) pipeline which crosses the town were damaged interrupting the water supply for two days.

The Baquedano water treatment plant suffered minor damage to the filter tank anchor bolts (see Figure 13). There was no interruption of the water supply for this town.

Figure 13 - Damage to filter tank at Baquedano

Sewerage

The sewerage system of Mejillones suffered minor damage to the main sewer, the treatment plant and the surge chamber of the submarine outfall sewer. The damage was concentrated near the coast and it was caused by settlement in the saturated sand filling (see Figure 14).

Treatment plant and surge chamber of outfall sewer.

Settlements of main sewer sections.

Figure 14 - Damage to sewerage system in Mejillones.

The sewerage system of Tocopilla was undamaged, but sewage could not flow into it after the earthquake because the entrance had been blocked by debris.

Seismic Intensities

Intensity values are determined by visual inspection based on the distribution of damage in different types of structures, classified according to vulnerability (see Table 2). To determine the intensities, the European Scale of Intensities (MSK) was used. This scale is based on the damage distribution for each vulnerability class and was adapted to the Chilean dwellings by Monge and Astroza (1989) as shown in Table 3.

Table 2. Vulnerability class

Vulnerability Class	Type of Structure
A	Adobe and Self-construction.
B	Unreinforced masonry. Braced wooden frame infills with adobe or low quality concrete ("Palo Ahogado").
C	Reinforced and confined concrete block masonry.

Table 3. Intensity degree based on damage distribution according to MSK (Monge and Astroza 1989).

Intensity Value	Class A		Class B		Class C	
	%	Damage Grade	%	Damage Grade	%	Damage Grade
5	5 95	1 0	100	0	100	0
6	5 50 45	2 1 0	5 95	1 0	100	0
7	5 50 35 10	4 3 2 1	50 35 15	2 1 0	50 50	1 0

8	5 50 35 10	5 4 3 2	5 50 35 10	4 3 2 1	5 50 35 10	3 2 1 0
9	50 35 15	5 4 3	5 50 35 10	5 4 3 2	5 50 35 10	4 3 2 1
10	75 25	5 4	50 35 15	5 4 3	5 50 35 10	5 4 3 2
11	100	5	75 25	5 4	50 50	5 4
12	-	-	100	5	100	5

Damage grades for different types of building are given in Tables 4 and 5. Both table are the product of the study carried out by Monge and Astroza in 1989 to determine intensity values based on the performance of dwellings made of adobe and diagonally braced wooden frames with adobe infills. These structures were the most damaged during the Tocopilla earthquake.

Table 4. Description of damage to adobe or masonry buildings

Damage Grade	**Description**
0	No damage.
1	Fine cracks in stucco.
2	Fine cracks in walls. Horizontal cracks in chimneys, tanks, pediments, cornices. Vertical cracks at intersection of walls.
3	Large and deep cracks in walls. Inclination or falling of chimneys, pediments, cornices. Vertical cracks in walls at intersections and some lean out-of-plumb. Diagonal cracks on walls are larger than 3 mm.
4	Partial collapse or total failure of a wall.
5	Total collapse.

Table 5. Description of damage for buildings with infill braced wooden frame

Damage Grade	*Description*
0	No damage.
1	Fine vertical and diagonal cracks on plaster. Vertical and diagonal cracks in the contact between braced wooden frame elements and infill.
2	Plaster falling.
3	Infill falling.
4	Partial or total collapse of a braced wooden frame.

Figure 15 and Table 6 summarize the estimated intensities for the towns visited and the resulting isoseismal map when the soil local condition corresponds to stiff soil, soil type II according the Chilean Seismic Code classification (INN, 1996). Much of the damage was concentrated between Quillagua and Antofagasta in the north-south direction, and as far as Sierra Gorda to the east. The earthquake severely affected the city of Tocopilla and to a lesser extent the city of Mejillones. Maximum intensities of VII (MSK), in the north-south direction, were observed along the coast immediately above the activated fault segment. The same distribution pattern is observed for lower intensity values.

Table 6. Estimated intensities, I_{MSK}

Place	Intensity	Place	Intensity
Quillagua	6.5	Sierra Gorda	5.0
Oficina Buena Esperanza	6.0	Baquedano	6.0
Tocopilla	7.0	Antofagasta	6.0
María Elena	7.0	Iquique	5.0
Pedro de Valdivia	6.0	Alto Hospicio	5.0
Gatico(1)	6.5	Calama	5.0
Cobija(1)	6.5	Taltal	5.0
Hornitos	6.5	Valparaíso	2.0
Mejillones	6.5	Viña del mar	2.0
Chacabuco	6.0	Santiago	2.0

(1) On rock.

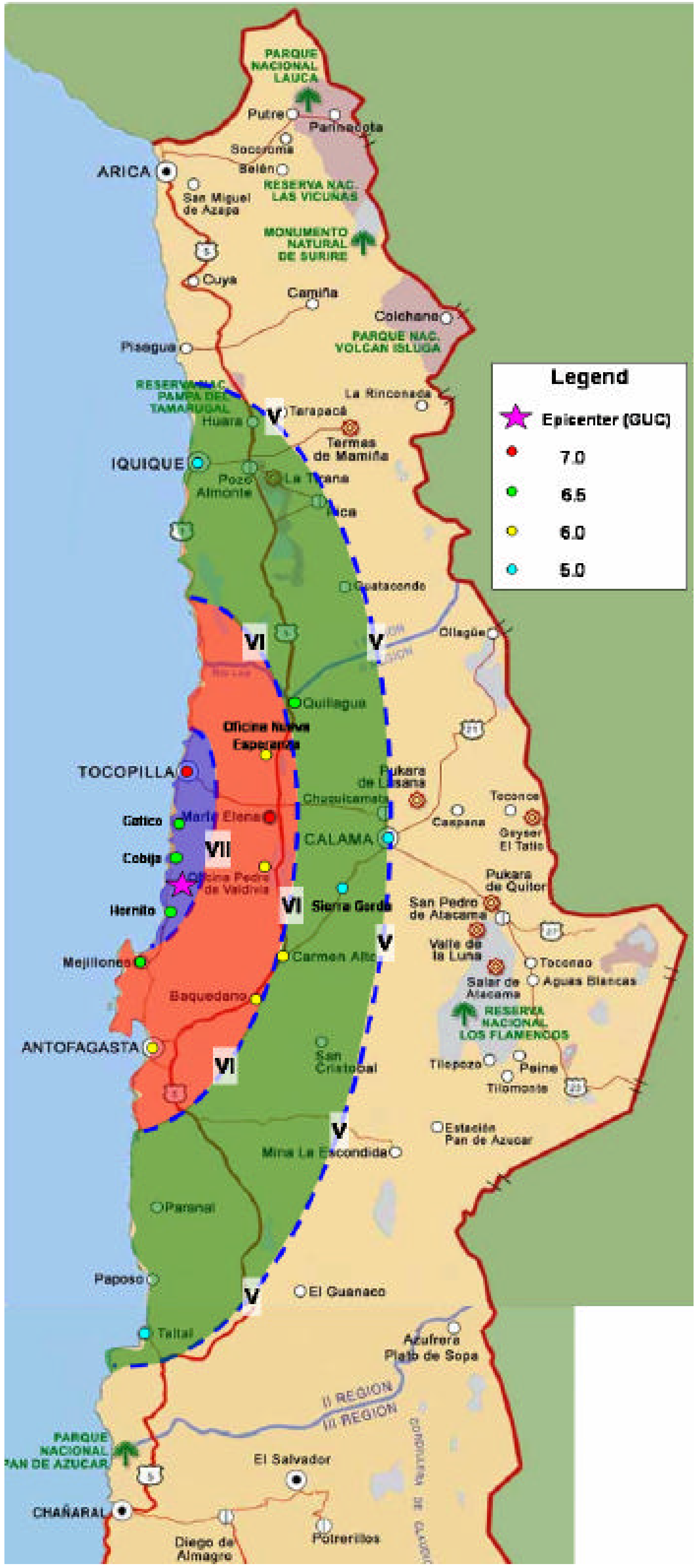


Figure 15 – Isoseismal map of the Tocopilla Earthquake, November 14th, 2007 when the soil local condition corresponds to soil type II according the Chilean Seismic Code classification (INN, 1996).

The variation in the intensity value (up ± 0.5 degree) in some sectors of Mejillones and Tocopilla can be explained by local soil conditions. The intensity value increases on recent alluvial deposits or uncontrolled fills confined by retaining walls, as shown by the effects on dwellings built on hillsides discussed earlier. On the other hand the intensity decreases on rock, as can be seen from the intensities in Cobija, Gatico and the south zone of Tocopilla (see Table 6).

To evaluate the impact of this moderate thrust earthquake on regional seismic hazard, the intensity values of the Tocopilla Earthquake, December 20th, 1967 (Ms=7.3), values obtained from the Chilean Seismological Service, and Tocopilla Earthquake, November 14th, 2007 (Ms=7.5), values give in Table 6, are compared in Figure 16 with the intensity attenuation relationship for Chilean earthquakes (Barrientos, 1980). Figure 16 shows that the estimated intensities of the Tocopilla 1967 and 2007 earthquakes are similar and that Barrientos' equation predicts intensity values greater than those estimated.

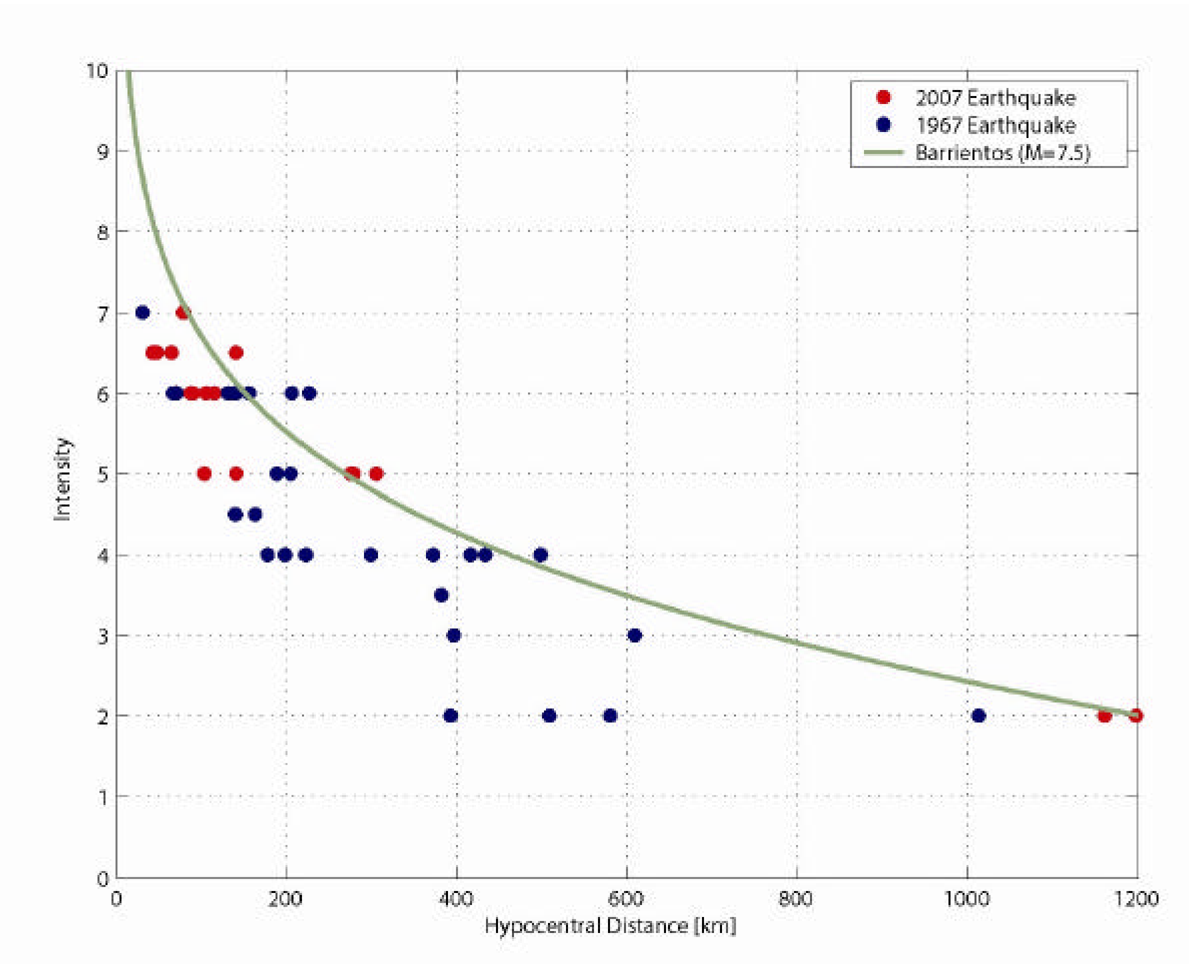


Figura 16 – Comparison of 2007 and 1967 Tocopilla Earthquake intensity data with intensity attenuation relationship proposed by Barrientos (Ms=7.5).

Comments

- The November 14th, 2007 Mw=7.7 event was a moderate interplate earthquake and its fault slip was localized at a depth between 30 and 40 km. Most of the early aftershocks were located towards the southern end of the rupture zone.

- Self-construction dwellings must be avoided in regions where this type of earthquake occurs since the assembly of the resisting elements (vertical an horizontal) is generally inadequate and they suffer sever damage, increasing the risk of injury.
- Well constructed confined concrete block masonry for low-cost dwellings is an efficient construction system to reduce earthquake damage.
- Damage increases dramatically when dwellings are located on recent alluvial deposits and uncontrolled fills in hillside residential areas.

Acknowledgments

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